Control of a Teleoperation System by State Convergence with Variable Time Delay

Julio C. Tafur, C. García, R. Aracil, R. Saltaren

I. Introduction

Teleoperation defines the idea of a user interacting with and manipulating a remote environment and has been an active research topic since Geortz and Thompson's demonstration of their first "local-remote" remote control in 1954 [1], teleoperation systems have been used for a number of different tasks, for example, material handling toxic or harmful, operation in remote environments such as submarine or space and perform tasks that require extreme precision and continue to play an increasingly important role for this type of applications in the future [2].

It consists of a local station that is the human operator, the local handler which sends commands to the remote site and also has a set of devices such as televisions and monitors that allow you to see the remote task. In the remote site is the robot that performs the task itself. Both stations are communicated through a communication channel that allows the flow of information in both directions.

During the teleoperation, the operator usually uses a visual presentation and a "local" handler (e.g. a phantom) to manually control a remote device of "slave" as a robotic arm.

Stability is an important aspect to build a teleoperation system with a high level of telepresence. Certainly, if a system exhibits unstable or closely unstable behavior, the illusion of the operator to be virtually present at the remote end can be destroyed, in addition to possibly make the task difficult or impossible to execute.

For applications of teleoperation in which the remote side is really remote, the time delay in the communication channel is a severe potential problem that can degrade the stability and performance. Over relatively short distances, the delay is not noticeable; however, when the local and remote manipulators are far away each other, the time delay is no longer negligible. This delay may be on the order of milliseconds to seconds or even minutes in operations in outer space.

At the same time, instability induced by the time delay, requires that the system be controlled in "open loop", reducing the operator to the technique of "wait and see", [3], [4], [5]. Por these situations, the general architecture of teleoperation not applies more.

Teleoperation systems can take advantage of the ubiquity, and a possible application can be a surgery at a distance where the surgeon is located far away from the patient. However, the use of the Internet and other networks of packages switching, such as Internet 2, impose variable time delays, making already established control schemes to develop solutions to deal with instabilities caused by these varying time delays.

Hence, the stability problem for time-delayed systems has received considerable attention in recent years.

The first work dealing with the problem of the delay was published in [6], where the system was operated in open loop, therefore not be observed problems of instability [7]. They conclude from several experiments that most operators took the strategy "move and wait" to correct the effects of the significant delay. In 1966 and later will determine that a time equal to or less than 50 ms delay can destabilize bilateral controllers [7], [8], [9].

The problem is due to the power generation in the communication channel that makes this component of the system is not passive [7]. One way to solve this problem is the addition of damping to the master and the slave to absorb the energy generated in the system. However, this technique does not guarantee stability and cause a poor performance [10], [11]. As an alternative, the bilateral control can be modified so that the communication channel acts as a line without loss of transmission [7].

In [12] the problem of bilateral teleoperation where the model of the operator is not passive is considered. Through the use of a PD control strategy without considering the delay shows that of nonlinear teleoperation system is asymptotically stable. When the delay of the communication channel is considered, for a range of coupling proportional gains, the positions converge asymptotically to a non-zero equilibrium point.

In [13] the feedback interconnection of non-linear systems with finite gain L2 is analyzed. In the case of constant delay shows classic small gain conditions to allow stable closed-loop connection which is delay-independent. In the case of variable delay, to ensure the independence of the stability with the delay, they proposed a small modified gain condition which depends of maximum rate of change of the delay.

In [14] proved that it is possible to achieve a stable behavior of teleoperation system with similar schemes to simple PD algorithms, even without the delayed action of the derivative, under the classic assumption of the passivity of the operator.

On the state convergence control technique [15], presents a state space formulation for a linear system of n order, through a control algorithm based on the feedback of position and speed of the manipulators signals, allow the remote manipulator to follow to the local handler through the state convergence even when there is a delay in the communication channel.

The method has been validated experimentally in teleoperator systems with a one degree of freedom [16] and two degrees of freedom [17]. They have carried out studies on adaptive control strategies based on this control scheme [18], designs considering delays in transmission [15], bilateral control by state convergence in teleoperated systems where the structure of the robot master differs from the slave [17].

In [19], we propose a novel control scheme based on state convergence for bilateral teleoperation of n degree-of-freedom (DOF) nonlinear robotic systems with constant time delay.

In this paper we improved the control scheme [19], analyzing the case of time-varying communication delay.

By choosing a Lyapunov-Krasovskii functional, we show that the local-remote teleoperation system is asymptotically stable

This new proposal improves the position signal with respect to [15] where signal drift problems arise. The main reason for this improvement is that control strategies are independent of parameter uncertainties in robot models, the human operator and the remote environment.

We demonstrate that the state convergence control scheme can be extended to a non-linear teleoperation system. In addition the strategy can be applied directly to a broad class of common control architectures of teleoperation.

The structure of the paper is, as follows: The mathematical model of the teleoperator system is described in section II. The control scheme is introduced in section III. Computer simulations of the proposed control scheme are presented in section IV, Experimental Test bed are show in section V, while the conclusions are given in section VI.

II. NONLINEAR MODEL OF ELEOPERATON SYSTEM

Let us consider a teleoperator system where both the local and remote are n-DOF manipulators described by Euler-Lagrange equations of the form

$$\begin{aligned} \mathbf{M}_l(\mathbf{q}_l)\ddot{\mathbf{q}}_l + \mathbf{C}_l(\mathbf{q}_l,\dot{\mathbf{q}}_l)\dot{\mathbf{q}}_l + \mathbf{g}_l(\mathbf{q}_l) &= \boldsymbol{\tau}_{lc} + \mathbf{F}_h \\ \mathbf{M}_r(\mathbf{q}_r)\ddot{\mathbf{q}}_r + \mathbf{C}_r(\mathbf{q}_r,\dot{\mathbf{q}}_r)\dot{\mathbf{q}}_r + \mathbf{g}_r(\mathbf{q}_r) &= \boldsymbol{\tau}_{rc} - \mathbf{F}_e \end{aligned} \tag{1}$$

Where $\ddot{\mathbf{q}}_i, \dot{\mathbf{q}}_i, \mathbf{q}_i \in \mathbf{R}^n$ corresponds to the acceleration, speed and position of the joint i = {l, r} where l and r sub-index represent the local and remote manipulator respectively. $\mathbf{M}_i(\mathbf{q}_i) \in \mathbf{R}^{n \times n}$ Is the Inertia matrix, $\mathbf{C}_i(\mathbf{q}_i, \dot{\mathbf{q}}_i) \in \mathbf{R}^{n \times n}$ represents the Coriolis and centrifugal forces matrix, $\mathbf{g}_i(\mathbf{q}_i) \in \mathbf{R}^n$ is the Gravitational forces vector, $\boldsymbol{\tau}_{ic} \in \mathbf{R}^n$ is the control torques signal, $\mathbf{F}_h \in \mathbf{R}^n$ represents the human operator interaction force and, finally, $\mathbf{F}_e \in \mathbf{R}^n$ is the environment interaction force.

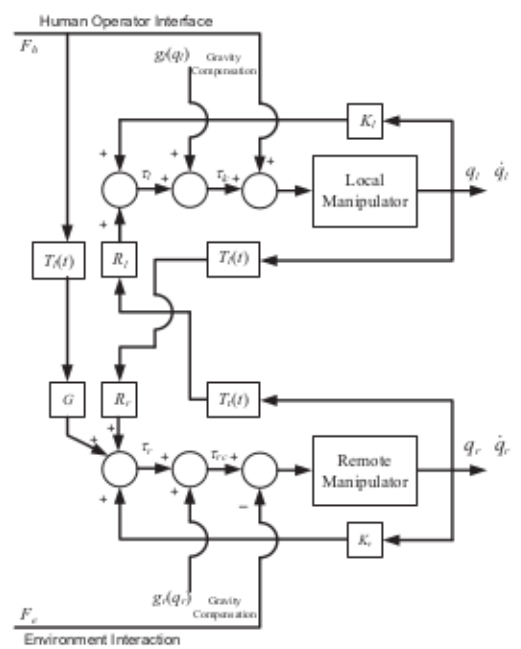

Figure 1. Block diagram of nonlinear control of teleoperation system considering delay.

In the block diagram of the teleoperator system, Fig. 1, the dynamics of the local and remote manipulator are given by (1).

Assumption 1: It is supposed that the interaction of the human operator with the local handle is a constant force in the following way [12]:

$$\mathbf{F}_h = \mathbf{F}_{op} \tag{2}$$

Assumption 2: The interaction of the environment with the remote manipulator is considered passive.

$$\mathbf{F}_e = \mathbf{K}_e \mathbf{q}_r + \mathbf{B}_e \dot{\mathbf{q}}_r \tag{3}$$

Where $\mathbf{K}_e$, $\mathbf{B}_e$ are definite positive matrix $\in \mathbf{R}^{n \times n}$

Assumption 3: It is supposed that $T_l(t)$ and $T_r(t)$ are continuously differentiable functions, which have an upper bound know T_i^+ defined by

$$0 \le T_i(t) \le T_i^+ < \infty, \quad \left|\dot{T}_i(t)\right| < 1, \quad i = l, r$$

In addition, the bound of round-trip delay communication channel is also known $T_{lr}^+ = T_l^+ + T_r^+$.

We proposed the control law (4) as shown in Fig. 1, this control law compensates for gravitational forces [20], so that the control torques $\boldsymbol{\tau}_{ic}$ are given by:

$$\boldsymbol{\tau}_{lc} = \boldsymbol{\tau}_l + \mathbf{g}_l(\mathbf{q}_l), \quad \boldsymbol{\tau}_{rc} = \boldsymbol{\tau}_r + \mathbf{g}_r(\mathbf{q}_r) \tag{4}$$

Replacing (4) in (1) yields:

$$\begin{aligned} \mathbf{M}_l(\mathbf{q}_l)\ddot{\mathbf{q}}_l + \mathbf{C}_l(\mathbf{q}_l, \dot{\mathbf{q}}_l)\dot{\mathbf{q}}_l &= \boldsymbol{\tau}_l + \mathbf{F}_{op} \\ \mathbf{M}_r(\mathbf{q}_r)\ddot{\mathbf{q}}_r + \mathbf{C}_r(\mathbf{q}_r, \dot{\mathbf{q}}_r)\dot{\mathbf{q}}_r &= \boldsymbol{\tau}_r - \mathbf{F}_e \end{aligned} \tag{5}$$

III. State Convergence Algorithm With Variable Time Delay

Consider a new version of the state convergence algorithm taking in count the time variable delay for nonlinear systems as show in Fig 1. The local and remote manipulator (1) is connected via a communication channel with a variable time delay, $T_i(t)$, $i = \{l, r\}$.

Consider the control algorithm for state convergence for the non-linear case, the coupling torque for the local and remote manipulator is given by:

$$\begin{aligned} \boldsymbol{\tau}_l &= \mathbf{K}_{l1}\mathbf{q}_l + \mathbf{K}_{l2}\dot{\mathbf{q}}_l + \mathbf{R}_{l1}\mathbf{q}_r(t - T_r(t)) + \mathbf{R}_{l2}\dot{\mathbf{q}}_r(t - T_r(t)) \\ \boldsymbol{\tau}_r &= \mathbf{K}_{r1}\mathbf{q}_r + \mathbf{K}_{r2}\dot{\mathbf{q}}_r + \mathbf{R}_{r1}\mathbf{q}_l(t - T_l(t)) + \mathbf{R}_{r2}\dot{\mathbf{q}}_l(t - T_l(t)) + G\mathbf{F}_{op}(t - T_l(t)) \end{aligned} \tag{6}$$

Where:

$$\mathbf{K}_l = [\mathbf{K}_{l1} \quad \mathbf{K}_{l2}], \mathbf{R}_l = [\mathbf{R}_{l1} \quad \mathbf{R}_{l2}], \mathbf{K}_r = [\mathbf{K}_{r1} \quad \mathbf{K}_{r2}], \mathbf{R}_r = [\mathbf{R}_{r1} \quad \mathbf{R}_{r2}]$$

Where: $\mathbf{K}_{l1}$, $\mathbf{K}_{l2}$, $\mathbf{R}_{l1}$, $\mathbf{R}_{l2}$, $\mathbf{K}_{r1}$, $\mathbf{K}_{r2}$, $\mathbf{R}_{r1}$ and $\mathbf{R}_{r2}$ are order nxn matrices constant diagonal positive definite. G is a constant.

From (2), (3), (5) and (6), one knows that the equilibrium points of the position of local and remote manipulator defined as $\bar{\mathbf{q}}_l \in \mathbf{R}^n$ and $\bar{\mathbf{q}}_r \in \mathbf{R}^n$, satisfy (7)

$$\begin{aligned} \mathbf{0} &= \mathbf{K}_{l1}\bar{\mathbf{q}}_l + \mathbf{R}_{l1}\bar{\mathbf{q}}_r + \bar{\mathbf{F}}_{op} \\ \mathbf{0} &= \mathbf{K}_{r1}\bar{\mathbf{q}}_r + \mathbf{R}_{r1}\bar{\mathbf{q}}_l + G\bar{\mathbf{F}}_{op}(t - T_l(t)) - \mathbf{K}_e\bar{\mathbf{q}}_r \end{aligned} \tag{7}$$

The main goal is to characterize and study the stability of nonlinear teleoperator system. In order to simplify the mathematical demonstration, it is convenient to settle the origin point, that is $[\mathbf{0}] \in \mathbf{R}^n$, like the equilibrium of the system. For doing this in the teleoperation system, it is necessary to apply a coordinate transformation like this:

$$\tilde{\mathbf{q}}_l(t) = \mathbf{q}_l(t) - \bar{\mathbf{q}}_l \rightarrow \mathbf{q}_l(t) = \tilde{\mathbf{q}}_l + \bar{\mathbf{q}}_l \tag{8}$$

$$\tilde{\mathbf{q}}_r(t) = \mathbf{q}_r(t) - \bar{\mathbf{q}}_r \rightarrow \mathbf{q}_r(t) = \tilde{\mathbf{q}}_r + \bar{\mathbf{q}}_r \tag{9}$$

In the new variables $\tilde{\mathbf{q}}_l(t), \tilde{\mathbf{q}}_r(t)$, the system has equilibrium at the origin.

Replacing (6), (7), (8) and (9) in (5) the dynamics of a bilateral teleoperation system in closed-loop is given by:

$$\begin{aligned} \mathbf{M}_l\ddot{\tilde{\mathbf{q}}}_l + \mathbf{C}_l\dot{\tilde{\mathbf{q}}}_l &= \mathbf{K}_{l1}\tilde{\mathbf{q}}_l + \mathbf{R}_{l1}\tilde{\mathbf{q}}_r(t - T_r(t)) + \mathbf{K}_{l2}\dot{\tilde{\mathbf{q}}}_l + \mathbf{R}_{l2}\dot{\tilde{\mathbf{q}}}_r(t - T_r(t)) \\ \mathbf{M}_r\ddot{\tilde{\mathbf{q}}}_r + \mathbf{C}_r\dot{\tilde{\mathbf{q}}}_r &= \mathbf{K}_{r1}\tilde{\mathbf{q}}_r + \mathbf{R}_{r1}\tilde{\mathbf{q}}_l(t - T_l(t)) + \mathbf{K}_{r2}\dot{\tilde{\mathbf{q}}}_r + \mathbf{R}_{r2}\dot{\tilde{\mathbf{q}}}_l(t - T_l(t)) - \mathbf{K}_e\tilde{\mathbf{q}}_r - \mathbf{B}_e\dot{\tilde{\mathbf{q}}}_r \end{aligned} \tag{10}$$

We proposes the following theorem which describes stability properties concerned with stability of equilibrium points of the closed loop teleoperation (10) with control algorithm given by (6).

Theorem 2.1:

For the bilateral teleoperation system given by (10), setting the control gains as

$$\begin{aligned} &\mathbf{K}_{l1} = -\mathbf{K}, \quad \mathbf{K}_{l2} = -(2\mathbf{K}_1 + \mathbf{K}_{ld}), \quad \mathbf{K}_{r1} = -\mathbf{K}, \quad \mathbf{R}_{l2} = 2\mathbf{K}_{ld} \\ &\mathbf{R}_{l1} = \mathbf{K}, \quad \mathbf{K}_{r2} = -(2\mathbf{K}_1 + \mathbf{K}_{rd}), \quad \mathbf{R}_{r1} = \mathbf{K}, \quad \mathbf{R}_{r2} = 2\mathbf{K}_{rd} \end{aligned} \tag{11}$$

Where: $\mathbf{K}_1$ and $\mathbf{K}$ are positive definite constant diagonal matrices. $\mathbf{K}_{ld}$ and $\mathbf{K}_{rd}$ are positive definite diagonal matrices given by

$$\mathbf{K}_{ld} = (1 - \dot{T}_r(t))\mathbf{K}_1 \qquad \mathbf{K}_{rd} = (1 - \dot{T}_l(t))\mathbf{K}_1 \tag{12}$$

If the following is satisfied:

$$\mathbf{K}_1 - \frac{\alpha_1}{2}\mathbf{K} - \frac{T_l^{+^2}}{2\alpha_2}\mathbf{K} > 0, \quad \mathbf{K}_1 - \frac{\alpha_2}{2}\mathbf{K} - \frac{T_r^{+^2}}{2\alpha_1}\mathbf{K} > 0 \tag{13}$$

Where α_1, α_2 and time delay T_i^+ for $i = l,r$ are scalar constants, then the equilibrium point at the origin is asymptotically stable.

$$\lim_{t\to\infty}\tilde{\mathbf{q}}_l = \lim_{t\to\infty}\tilde{\mathbf{q}}_r = \lim_{t\to\infty}\dot{\tilde{\mathbf{q}}}_l = \lim_{t\to\infty}\dot{\tilde{\mathbf{q}}}_r = \mathbf{0}$$

For the stability analysis considering the variable delay, we define V, a positive definite functional, for the system as:

$$V\left(\dot{\tilde{\mathbf{q}}}_l,\dot{\tilde{\mathbf{q}}}_r,\tilde{\mathbf{q}}_l,\tilde{\mathbf{q}}_r\right)=\frac{1}{2}\dot{\tilde{\mathbf{q}}}_l^{\mathrm{T}}\mathbf{M}_l\dot{\tilde{\mathbf{q}}}_l+\frac{1}{2}\dot{\tilde{\mathbf{q}}}_r^{\mathrm{T}}\mathbf{M}_r\dot{\tilde{\mathbf{q}}}_r+\frac{1}{2}(\tilde{\mathbf{q}}_l-\tilde{\mathbf{q}}_r)^{\mathrm{T}}\mathbf{K}(\tilde{\mathbf{q}}_l-\tilde{\mathbf{q}}_r)$$
$$+\frac{1}{2}\tilde{\mathbf{q}}_r^{\mathrm{T}}\mathbf{K}_e\tilde{\mathbf{q}}_r+\int_{t-T_l(t)}^{t}\dot{\tilde{\mathbf{q}}}^{\mathrm{T}}(\xi)\mathbf{K}_1\dot{\tilde{\mathbf{q}}}_l(\xi)d\xi+\int_{t-T_r(t)}^{t}\dot{\tilde{\mathbf{q}}}_r^{\mathrm{T}}(\xi)\mathbf{K}_1\dot{\tilde{\mathbf{q}}}_r(\xi)d\xi$$

Where $T_i(t)$ for $i = l,r$ is the variable delay of communication channel and $\mathbf{K}$, $\mathbf{K}_e$ y $\mathbf{K}_1$, positive definite constant diagonal matrices.

Analyzing the time derivative of the above Lyapunov functional (Lyapunov-Krasovskii functional) along the system trajectories described by (10), we show that the local-remote teleoperation system is asymptotically stable.

A. Reflection Static Force

Consider the non-linear teleoperator system described by (5) and the control law given by (6) for the range of control given by (13), you have the following:

$$\mathbf{0}=\overline{\mathbf{F}}_{op}+\mathbf{K}_{ll}\overline{\mathbf{q}}_l+\mathbf{R}_{ll}\overline{\mathbf{q}}_r$$

From (11) $\mathbf{K}_{ll}=-\mathbf{K},\quad \mathbf{R}_{ll}=\mathbf{K}$, $\mathbf{K}_{rl}=-\mathbf{K},\quad \mathbf{R}_{rl}=\mathbf{K}$

$$\overline{\mathbf{F}}_{op}=\mathbf{K}(\overline{\mathbf{q}}_l-\overline{\mathbf{q}}_r)$$

$$\mathbf{0}=-\overline{\mathbf{F}}_e+\mathbf{K}_{rl}\overline{\mathbf{q}}_r+\mathbf{R}_{rl}\overline{\mathbf{q}}_l+G\overline{\mathbf{F}}_{op} \tag{14}$$

$$\mathbf{0}=-\overline{\mathbf{F}}_e+\mathbf{K}(\overline{\mathbf{q}}_l-\overline{\mathbf{q}}_r)+G\overline{\mathbf{F}}_{op}$$

$$\overline{\mathbf{F}}_{op}=\frac{1}{(1+G)}\overline{\mathbf{F}}_e \tag{15}$$

B. Local-Remote Manipulator Position Coordination

If $\mathbf{F}_{op}=\mathbf{F}_e=\mathbf{0}$, (14) and (15) can be written as $\overline{\mathbf{q}}_l-\overline{\mathbf{q}}_r=\mathbf{0}$.

This implies that the equilibrium points of the local and remote manipulator are identical. Then, the position coordination error $\tilde{\mathbf{q}}(t)=\mathbf{q}_l(t)-\mathbf{q}_r(t)$

Tends to zero like $\lim_{t\to\infty}\tilde{\mathbf{q}}(t)=\lim_{t\to\infty}(\mathbf{q}_l(t)-\mathbf{q}_r(t))=\mathbf{0}$

Then, there is positions coordination between the local and remote manipulator.

IV. Simulation

The control law (4) and (6) applied to the dynamics of the teleoperation system (1) have been simulated using Matlab™ and Simulink®. For a local manipulator, we will use a PHANTOM Omni® haptic device from Sensable Technologies. For a remote manipulator we employed a planar serial arm with three degrees of freedom, actuated by DC motors, [20]:

To obtain the remote manipulator dynamic model, we parameterize the manipulator, for this it is necessary to calculate the mass, center of gravity and the inertia of the links referring to each one of the systems coordinates of the links. These parameters can easily obtain them with a computer-aided design program.

The parameters obtained from the three links are shown in Table I. These include the mass, the centroid and the principal moments of inertia [20].

TABLE I. MANIPULATOR ARM JOIN PARAMETERS

Parameter	*Link 1*	*Link 2*	*Link 3*
Length between axis (mm)	210.8	159.6	N/A
Mass (Kg)	0.429	0.214	0.015
Centroid x (mm)	-82.337	-70.7	0
Centroid y (mm)	0	0	0
Centroid z (mm)	-12.398	17.720	57.997
I_{xx} (Kg mm^2)	167,929	39.977	6.355
I_{yy} (Kg mm^2)	2595	724.650	6.355
I_{zz} (Kg mm^2)	2583	737.257	3.695

Once have the parameters of the robot, it is to replace them in the dynamic model.

$$\mathbf{M}_l(\mathbf{q}_l)\ddot{\mathbf{q}}_l+\mathbf{C}_l(\mathbf{q}_l,\dot{\mathbf{q}}_l)\dot{\mathbf{q}}_l+\mathbf{g}_l(\mathbf{q}_l)+\mathbf{f}_l(\dot{\mathbf{q}}_l)=\boldsymbol{\tau}_{lc}+\mathbf{F}_{op}$$
$$\mathbf{M}_r(\mathbf{q}_r)\ddot{\mathbf{q}}_r+\mathbf{C}_r(\mathbf{q}_r,\dot{\mathbf{q}}_r)\dot{\mathbf{q}}_r+\mathbf{g}_r(\mathbf{q}_r)+\mathbf{f}_r(\dot{\mathbf{q}}_r)=\boldsymbol{\tau}_c-\mathbf{F}_e$$

$\mathbf{f}(\dot{\mathbf{q}})\in\mathbf{R}^n$ is a static model of joints friction, defined by [21]:

$$\mathbf{f}_l(\dot{\mathbf{q}}_l)=\mathbf{f}_r(\dot{\mathbf{q}}_r)=\mathbf{f}(\dot{\mathbf{q}})=\begin{bmatrix}0.05 & 0 & 0\\ 0 & 0.05 & 0\\ 0 & 0 & 0.05\end{bmatrix}\begin{bmatrix}\dot{\mathbf{q}}_1\\ \dot{\mathbf{q}}_2\\ \dot{\mathbf{q}}_3\end{bmatrix}$$

The inertia matrix $\mathbf{M}_r$, the coriolis and centrifugal forces matrix $\mathbf{C}_r$, the force of gravity matrix $\mathbf{g}_r$ of remote manipulator are defined by:

$$M_{12r}=M_{21r}=0.012801+0.01588\cos(q_2)$$
$$M_{13r}=M_{31r}=0.0014037$$
$$M_{22r}=0.012801$$
$$M_{23r}=M_{32r}=0.0014037$$
$$M_{33r}=0.0014037$$

$$C_{11r} = C_{13r} = 0$$
$$C_{12r} = -0.01588\sin(q_2)(\dot{q}_2 + 2\dot{q}_1)$$
$$C_{21r} = 0.01588\sin(q_2)\dot{q}_1$$
$$C_{22r} = C_{23r} = 0, \quad C_{31r} = C_{32r} = C_{33r} = 0$$

$$g_{1r} = -0.739\sin(q_1)\cos(q_2) - 0.739\cos(q_1)\sin(q_2) - 1.6409\sin(q_1)$$
$$g_{2r} = -0.739\cos(q_1)\sin(q_2) - 0.739\sin(q_1)\cos(q_2)$$
$$g_{3r} = 0$$

A. *Internet Communications*

Uncertain transmission time delay and data loss problems are not avoidable for any Internet-based application. In particular, Internet data have random time-delay and packet losses which depend on the characteristics of the network and on its load.

The controller is designed when the upper bound of the first derivative of the delay is known.

Two transport protocols usually applied to the development of networked robot applications, one which is packet oriented (User Datagram Protocol, UDP) and the other which is stream oriented (Transport Control Protocol, TCP).

The TCP protocol is defined as a reliable protocol while the UDP protocol is defined as unreliable [22]. TCP is suitable for applications that require guaranteed delivery (e.g., static data transfer), where delay is not of the first concern, but accurate and complete reception may be the more important thing [23].

On the other hand, the User Datagram Protocol (UDP) is connectionless. Data is sent in packets, there is no error correction or detection above the network layer and there is no handshake. UDP is commonly applied to the transmission of low level commands. These commands are related to low-level control robot movements which demand different network requirements.

Since TCP features introduce and excessive overhead and cannot be excluded by the user, the UDP protocol is preferred for constant data-flow applications such as control and multimedia sessions.

For time delay selection we use the results given in [24], where the delay parameters of an Internet segment are identified by probing the network.

TABLE II. TIME DELAY PARAMETERS FOR TYPICAL INTERNET CONNECTION

Host	*Distance (Km)*	*Average Delay (ms)*	*Standard Deviation*	*Loss rate*
1. Local	0.05	0.998	0.715	0.00
2. Same Domain	30	8.10	5.35	0.08
3. Different City	150	17.20	9.74	0.80
4. Different Continent	10000	326.3	27.20	41.4

Table II shows the delay parameters of connections of various lengths measured with 100 ms probes. The duration of the measurement is approximately 1000 s and it has been performed during regular office hours.

These experimental results are influenced by several parameters, i.e., distance, number of traversed nodes, and network load [24].

For the simulation, we assume the time delay in both directions is equal $T_r^+ = T_l^+ = 0.45\,\text{sec}$. Hence the upper bound of the round-trip delay in communication is $T_{lr}^+ = 0.9\,\text{sec}$. Fig. 2 shows the time delay used in simulation.

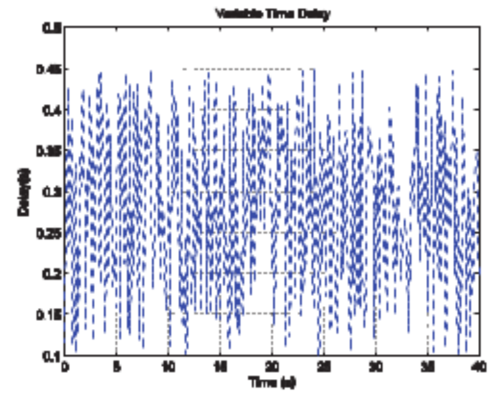

Figure 2. The variable time delay ranges from 0 to 40 sec.

The force (torque) applied by the human operator to the joints of the local manipulator to move the remote manipulator is show in Fig. 3.

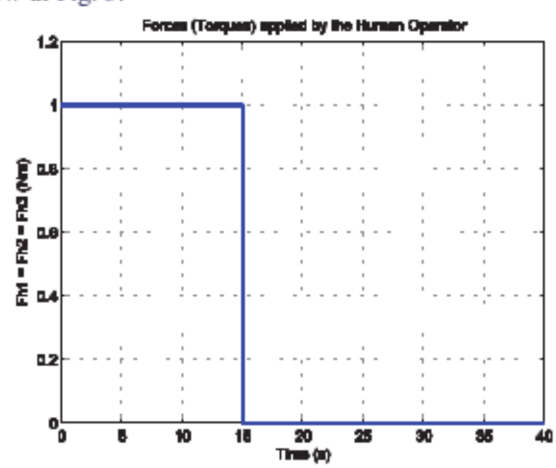

Figure 3. Force (Nm) applied by the human operator.

B. *Gain Parameters*

Letting $\alpha_1 = T_r^+, \alpha_2 = T_l^+$, $|\dot{T}_i(t)| = \dot{T}_{max} = 0.8$ the gains $\mathbf{K}$ and $\mathbf{K}_1$ are calculated using relation (13) as:

$$\mathbf{K}_1 = \begin{bmatrix} 40 & 0 & 0 \\ 0 & 30 & 0 \\ 0 & 0 & 10 \end{bmatrix}, \quad \mathbf{K} = \begin{bmatrix} 80 & 0 & 0 \\ 0 & 60 & 0 \\ 0 & 0 & 20 \end{bmatrix}$$

Then, the controller's gains values parameters $\mathbf{K}_{l1}$, $\mathbf{K}_{l2}$, $\mathbf{K}_{r1}$, $\mathbf{K}_{r2}$, $\mathbf{R}_{l1}$, $\mathbf{R}_{l2}$, $\mathbf{R}_{r1}$, $\mathbf{R}_{r2}$, $\mathbf{K}_{ld}$ and $\mathbf{K}_{rd}$ are determined by (11) and (12), in addition $G = 1$.This values are the same for all the simulations.

Simulations have been carried out considering two cases: the remote manipulator does not interact with the environment and the remote manipulator interacts with the environment. Their objective is to show that the original controllers proposed on this work do provide position tracking.

C. *Case A: Without Environment Interaction*

a)

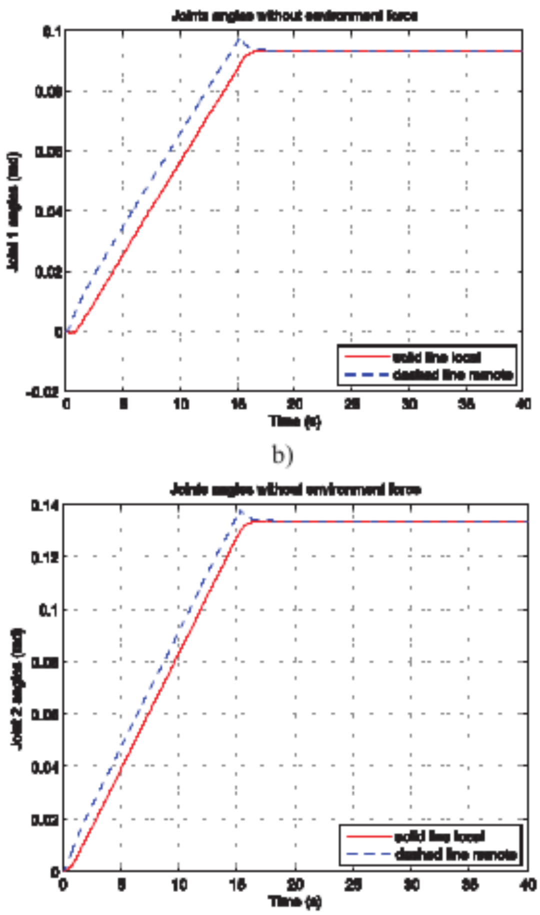

Figure 4. Angular position of local and remote manipulator: a) Joint 1; b) Joint 2.

As seen from the simulation waveforms in Figs. 4 for the case when the remote manipulator does not interact with the environment, i.e. interaction force is zero; better tracking performance can be obtained by using the proposed control scheme. The joint angles of the remote manipulator (dashed line) accurately track those of the local manipulator (solid line). When the operator force is zero, at $t = 15$ sec, the position coordination error $\tilde{\mathbf{q}}(t) = \mathbf{q}_l(t) - \mathbf{q}_r(t)$ tends to zero and the equilibrium points of the position of local and remote manipulator $\bar{\mathbf{q}}_l$ and $\bar{\mathbf{q}}_r$ are identical.

The stability of teleoperator in closed loop with the controllers of this scheme (6) has been established in Theorem 2.1. The controller guarantees a stable behavior under time delays, and also ensures position tracking.

D. *Case B: Environment Interaction*

a)

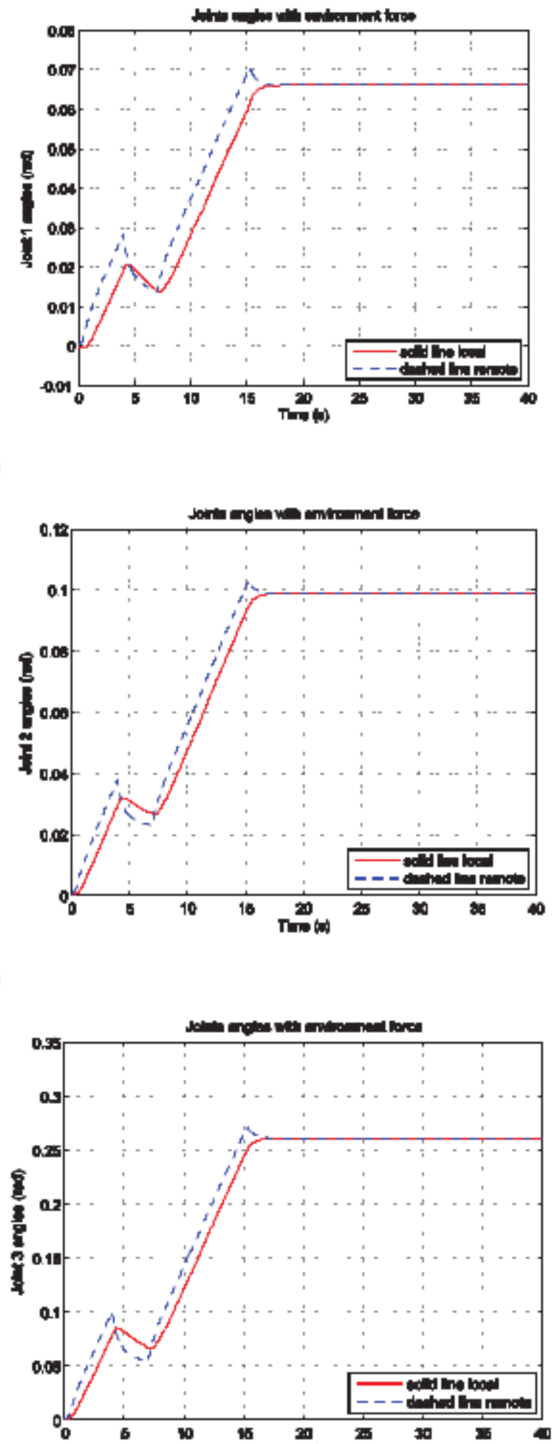

Figure 5. Angular position of local and remote manipulator: a) Joint 1; b) Joint 2; c) Joint 3.

In order to assess the stability of the contact in simulations, we considered a soft environment modeled by means of a spring -damper system, with the spring and damper gains as:

$$\mathbf{K}_e = \begin{bmatrix} 25 & 0 & 0 \\ 0 & 25 & 0 \\ 0 & 0 & 25 \end{bmatrix} \mathrm{N/m}, \quad \mathbf{B}_e = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathrm{N \cdot s/m}$$

Fig. 5 shows the joints positions of the local and remote manipulator.

When the remote manipulator does not contact with the environment (0 - 4s and 10-40 s) position coordination of the local and remote manipulator position is achieved.

Simulations cannot replicate the quality of the human perception, but they provide useful indications about performance of the controller.

V. EXPERIMENTAL TEST BED

In this section, we show the experimental setup of local-remote teleoperation system, which will be use to confirm the validity of the proposed control scheme, see Fig. 6.

This local - remote bilateral-teleoperation structure allows a human operator to drive the remote manipulator, by manipulating the PHANTOM Omni haptic device whose movements are repeated by the remote manipulator.

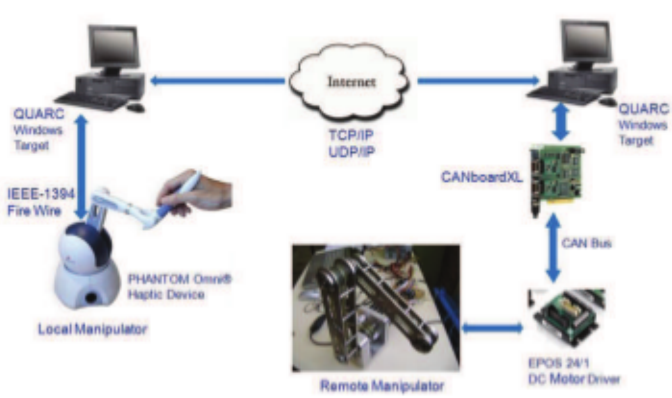

Figure 6. Teleoperation system structure.

The contact forces generated by the interaction between the physical environment and the robot manipulator are reflected to the human operator via the haptic device.

A. Local Manipulator

The local manipulator is a 6 DOF haptic device PHANTOM Omni® from SensAble Technologies. It is a PC-based six-revolute-joint arm. An onboard IEEE-1394 FireWire port provides fast communication to a PC. Quanser's QuaRC control software solution includes a PHANTOM Omni blockset for MATLAB's Simulink environment. The Omni Simulink block sends force commands to the Omni's motors and receives 6-DOF positions. Its stylus may be handled by an operator.

In this case a setup contains a few feedback signals and a few control signals. Even if 32-bit values are used, a typical data packet (read or write) would be on the order of 100 bytes. Thus, a three-joint manipulator arm would require about 600 bytes (3*200); in the case of use a control frequency of 10 kHz, this would require a bus bandwidth of 6 MBytesps, or approximately 50 Mbps. This is satisfied for high-speed serial networks, such as IEEE 1394 (up to 400 or 800 Mbps for 1394a or 1394b, respectively).

Latency of the data transfers introduces a time delay in the control computations, which compromises performance and can lead to instability. Latency is primarily determined by overhead in the protocol and the software drivers. The IEEE 1394 should provide the lowest latency, especially when used with a real-time operating system.

B. Remote Manipulator

The Remote manipulator is three degrees of freedom planar serial manipulator, Fig. 7. The motors are located at the base, for this reason the arm is implemented with a series of transmissions leading the movement to each of the joints.

Figure 7. Serial Manipulator Structure.

Transmissions are performed using bearings and toothed belts polyurethane with steel fibers which provide the Sync feature which is essential for the control of the robot [21]. The material used for the manufacture of the links in the arm is stainless steel, aluminum has been considered for other elements. The developed mechanical structure is compact and lightweight.

The joint angles and joint velocities are detected by encoders MR 228177 (128 counts per turn). Control input signals are sent to each electric brushless DC motors via a motor controller EPOS 24/1 for maxon motor.

Because there are multiple devices EPOS, these devices are connected in a CAN network and are commanded from the PC using a CANboardXL V1.0 and software CANoe V7.6 from Vector Informatik.

In order to verify the performance of the real-time communication, the theoretically possible amount of data has been calculated. Assuming, that one CAN message consists on an 11-bit Identifier, 1-bit RTR, 4-bit for the length data and at most of eight bytes of data. Therefore, the whole message represents at most 10 bytes (80 bits). The CANboardXL allows a maximum speed of 1 M bits per second (bps), but we use 500,000 bits per second (bps). Then, the maximum amount of CAN messages they can be sent through the CAN Bus in 6,250 message/s.

Typically, at the end of each control loop 4 CAN messages have to be sent to the devices in the CAN network (three to the EPOS Motor Controllers and one SYNC object). This results in the theoretically possible sampling frequency of 1,562.5 Hz.

C. Real-Time Control

The host and remote computer implement the state convergence control scheme (6) under MATLAB/Simulink using QUARC software mounted on Windows XP-based PC.

This Simulink model uses the software QUARC in order to allow the interface with the haptic device and to realize touch-over-network applications in real-time.

VI. CONCLUSIONS

Taking into account time-varying communication delay, we propose a control scheme that guarantees the stability of the overall system.

The proposed scheme also guarantees that the remote manipulator tracks the delayed local manipulator trajectory.

The Lyapunov-Krasovskii functional is used to analyze delay-dependent stability and derive the stability criteria.

Finally, the simulation is presented to show the effectiveness of the main results.

Future works will aim at the evaluation of the proposed scheme on a local-remote experimental test bed.

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